TRANSVERSE BEAM DYNAMICS OF AN 8 MeV ELECTRON LINAC

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Abstract

The IPM Electron Linac is an 8 MeV (upgradable to 11 MeV) electron linear accelerator under development at the Institute for Research in Fundamental Science (IPM), Tehran, Iran. The linac is mainly regarded as a research project providing hands-on experience in the accelerator science and technology. However, it could serve as an x-ray source or play the injector role for a larger facility. The linac consists of a thermionic gun followed by a travelling wave buncher joined to two accelerating tubes. The transverse focusing is provided by the solenoid magnets over the buncher and the accelerating structures. Using the code ASTRA, the transverse beam dynamics is studied and optimized in order to limit the RF emittance. Particularly, the effect of coupler asymmetry is investigated, a beam dynamics design of the solenoid channel is presented, and the effect of the solenoid misalignment on the beam quality is examined.

INTRODUCTION

The IPM Electron Linac is an 8 MeV (upgradable to 11 MeV) electron linear accelerator under development at the Institute for Research in Fundamental Science (IPM), Tehran, Iran. As the first practice in the design and construction of the particle accelerators in IPM, the main purpose of this project is to provide hands-on experience in the accelerator science and technology. Although no well-defined application is foreseen for the resulting electron beam, the linac could serve as an x-ray source or play the injector role for a larger facility. The project is meeting its final stages and the linac commissioning is due in a few months.

The layout of the linac is shown in Fig. 1. A thermionic gun provides a beam with an energy and current up to 50 keV and 10 mA, respectively. The gun is followed by a travelling wave (TW) buncher joined to two TW constant impedance accelerating tubes. The buncher is nearly 35 cm in length and each accelerating tube is 60 cm. The beam energy at the end of the buncher, first, and second tube would be 1.4 MeV, 4.7 MeV, and 7.8 MeV, respectively. A third tube can be added if a higher energy is required. The beam dynamics and RF design of the buncher and the accelerating tubes are described in [1] and the construction process in [2-4].The buncher and the accelerating tubes are embedded in a solenoidal field providing the transverse focusing. This focusing channel is referred as the main focusing channel in this paper. Two small solenoids serve as a matching cell between the gun and the main focusing channel. In the transverse plane the main issue is limit the RF emittance.

In the following, the transverse beam dynamics of the linac is reviewed shortly. First, we discuss a little on the RF emittance. The effects of the field asymmetry induced by the couplers are investigated afterwards. We then go through some beam dynamics optimisations in order to design the solenoid channel. Finally, the effect of the solenoid misalignments is examined. The Beam dynamics simulations presented in this paper have been carried out by the code ASTRA.

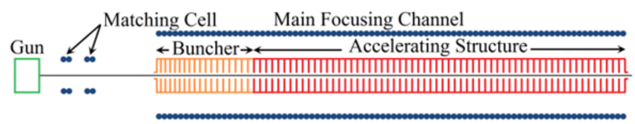

Figure 1: General layout of the IPM linac.

RF INDUCED EMITTANCE GROWTH

In a TW structure in which the principle is dominant the transverse force acting on a particle is given by

$$F_r = -\frac{e\omega E_0}{2c}\frac{\left(1-\beta\beta_{ph}\right)}{\beta_{ph}} r\sin\theta\,, \tag{1}$$

$$\theta = \omega t - \int_0^z \frac{\omega}{\beta_{ph}\left(z'\right)c}dz'\,. \tag{2}$$

E_0 is the longitudinal electric field amplitude of the principle wave, β_{ph} the normalised wave velocity of the structure and θ the RF phase seen by the particle.

As a time dependent force, the RF defocusing violates the Liouville's theorem and allows for the emittance growth. The RF defocusing and the resulting emittance growth vanishes as $\beta\beta_{ph}$ tends to 1 or in the case of on crest acceleration. Therefore, the RF emittance is most a concerning issue in the buncher. With an effective focusing, however, one can limit the beam size to reduce the average particle distance with respect to axis, r, resulting in weaker RF defocusing [see Eq. (1)] and hence a smaller emittance growth.

The beam current is low enough to ignore the space charge emittance. We obtained rather the same results turning on or off the space charge in the simulations.

COUPLER ASYMMETRY

The presence of the RF couplers, breaking the azimuthal symmetry, provides non-zero transverse field components on axis. This asymmetry extends over a few cells near the couplers as shown in Fig. 2. These components produce additional time dependent forces causing an additional emittance growth. Without a focusing field, the normalized rms emittance at the end of third cell is 8.4 µm and 13.9 µm in the horizontal and vertical directions, respectively. In the other hand, they induce an RF kick in the vertical direction. For a continuous beam with uniform phase distribution, one expects no net kick. With the bunching taking place, however, the beam receives a net vertical kick. The average vertical angle of the particles at the end of third cell is 4.6 mrad. Figure 3 shows the beam cross section and the corresponding horizontal and vertical particle distribution at the end of third cell.

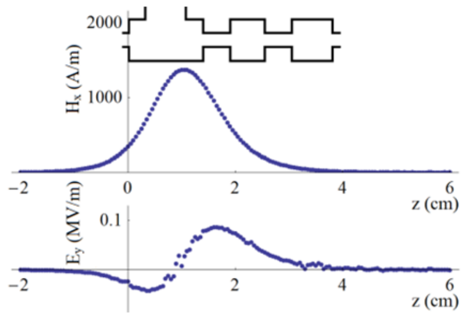

Figure 2: Transverse field components on axis near the input coupler.

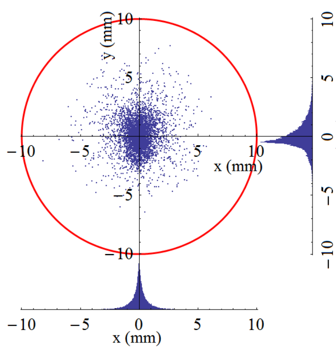

Figure 3: Beam cross section and the horizontal and vertical particle distribution at the end of third cell.

For this simulation the solenoid focusing is turned off in order to study the pure effect of the RF fields. With a solenoidal field, the horizontal and vertical motions are no longer decoupled. Due to the Larmor motion of the particles, the coupler asymmetry emittance will occur in both directions.

A similar effect is associated with the output coupler; however, with practically no emittance growth because the beam is bunched and all particles see rather the same transverse force.

SOLENOID CHANNEL DESIGN

The initial beam parameters are obtained by CST simulation of the electron gun. The beam has a waist at 17 cm downstream the cathode with an rms size of 0.30 mm and normalised emittance of 1.18 µm. The solenoid channel is designed with the goal of controlling the beam size and limiting the emittance growth. The beam envelope compared to the aperture size should be small enough to keep the beam loss in an acceptable limit. By the beam envelope in this paper we mean the rms beam size. The ratio of the aperture size to the rms beam size should not be less then around seven [7]. With the aperture size of 10 mm the envelope should not exceed around 1.5 mm. The evolution of the beam envelope, a, with respect to the longitudinal position z is best described by the envelope equation as follows [5, 6]:

$$a'' + \frac{(\gamma\beta)'}{\gamma\beta}a' + k_B^2 a - k_{RF} a - \frac{\varepsilon_{rms}^2}{a^3} = 0 , \tag{3}$$

$$k_B = \frac{eB}{2\gamma m \beta c} , \tag{4}$$

$$k_{RF} = \frac{e\omega E_0 \sin\theta_{av}}{2mc^3\gamma^3\beta^3} . \tag{5}$$

B is the solenoidal field on axis and θ_{av} the average RF phase seen by the particles in a bunch. Although, the coupler breaks the beam azimuthal symmetry, in strong enough focusing fields, the beam parameters are not very different in horizontal and vertical direction. The beam parameter represented in the following is the average of vertical and horizontal quantities.

An especial solution of interest to the envelope equation is one with $a'' = 0$ and $a' = 0$ through the channel. Such a solution with a constant beam size is known as the matched beam and the corresponding channel as the uniform focusing channel. The matched beam solution is of particular interest in the case of intense beams where the envelope oscillations contribute to the space charge induced emittance growth. Although, the space charge effect is ignorable in our case, investigating the uniform focusing channels would be very inspiring for the design purpose. The solenoidal field on axis required for a uniform focusing channel is given by (see Eqs. (3-5))

$$B = \frac{2mc}{e}\sqrt{\frac{e\omega E_0 \sin\theta_{av}}{2mc\gamma\beta c^3} + \frac{(\gamma\beta\varepsilon_{rms})^2}{a^4}} . \tag{6}$$

As well as supplying the correct field map the beam should be launched with appropriate initial condition that is ensured by the matching cell. Although the required field map is given in Eq. (6) the uniform focusing channel design is not very straightforward because it needs a prior knowledge of the emittance of the matched beam which is not available. With an iterative process described in [8] however, one can find the ideal field map required. The uniform focusing channel is designed for three different target beam sizes and the results are illustrated in Fig. 4. According to this figure the emittance growth is smaller for a beam of smaller size as expected. However, we need to provide a stronger focusing field. In this sense there is no limit to restrict the beam emittance growth. On the other hand, the most part of the emittance growth is associated to the initial parts of the buncher where the long and low energy bunch is launched at zero crossing. In the accelerating tubes, however, the beam emittance is rather constant independent of the beam size. The study of the uniform focusing channel suggests the following strategy for the solenoid channel design. We apply a stronger focusing over the buncher and relatively a smaller one for the accelerating tubes. If we provide strong enough field

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over the buncher we can even leave the second accelerating tube without any focusing. We use uniform winding in order to simplify the construction process. Although this will result in a beam size variation trough the structure, it does not contribute the emittance growth because the space charge forces are ignorable. Following an extensive beam dynamics optimisation, fields of 1200 G and 800 G are chosen over the buncher and tubes, respectively, compromising between the cost and the beam quality. The solenoids will be designed to produce such a field with their maximum tolerated current. However, 20% below the maximum current will be chosen as a prudent operating point. Figure 5 (up diagrams) shows the beam cross section at the end of linac for channels with its maximum field, 20%, and 40% below the maximum. The corresponding beam emittances are 5.6 µm, 6.6 µm, and 23.8 µm, respectively.

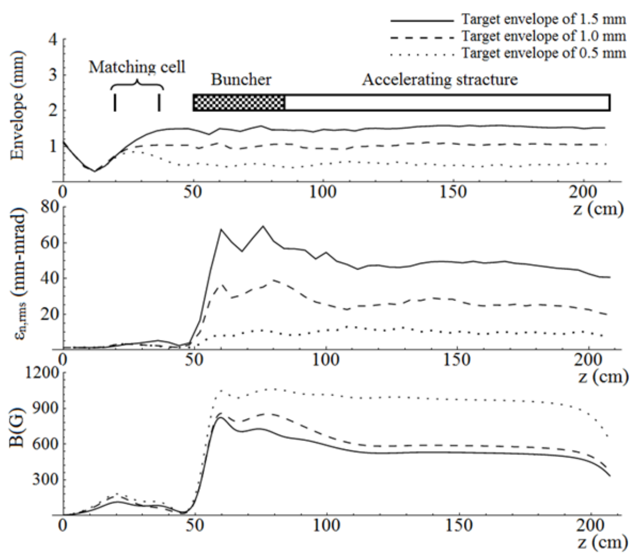

Figure 4: RMS beam size and emittance evolution in a uniform focusing channel for three different target beam size and the corresponding ideal field maps.

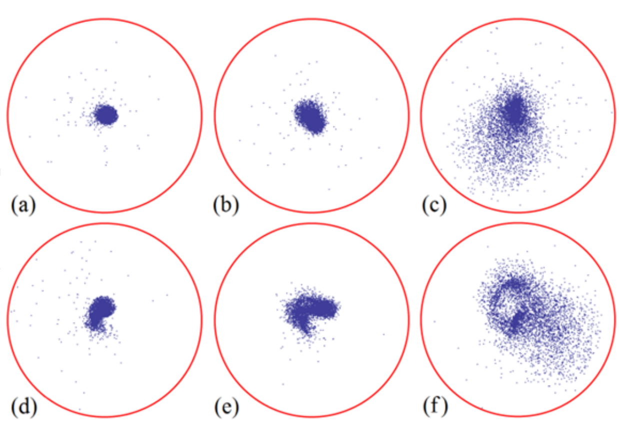

Figure 5: The beam cross section at the end of linac for a channel with the maximum current (left diagram), 20% below the maximum (middle diagram), and 40% below the maximum (right diagram). The bottom diagrams are the same for the case of 1 mm solenoid offset.

As can be seen from the Fig. 5 **(**diagram (c)**)** at the field level 40% below the maximum, the beam border comes close to the vacuum chamber wall. This shows a kind of lower limit for the required focusing strength.

SOLENOID CHANNEL DESIGN

Although solenoids are known as magnets offering very uniform magnetic field their misalignments can deteriorate the beam quality. This comes from the fact that the radial coordinate of the solenoid fringe field plays a role in the solenoid focusing [6]. Like any focusing elements, solenoids exert a radial force on particle drawing them on average towards its axis. Therefore, any misalignment in the solenoid magnets results in a beam offset from cavity axis. This in turn results in a larger particle distance with respect to cavity axis and hence a larger emittance growth. Bottom diagrams of Fig. 5 illustrate the beam cross section with a 1 mm solenoid offset. For the maximum field strength the beam emittance increases 41% and 122% for solenoid offsets of 0.5 mm and 1 mm, respectively. The solenoid misalignment is most a concerning issue for those over buncher. At higher energies with $\beta\beta_{ph} \approx 1$ the transverse RF forces vanishes with no more emittance growth even with solenoid misalignment.

CONCLUSION

Transverse beam dynamics of the IPM linac is studied and optimised in order to limit the RF emittance. The coupler asymmetry results in an unavoidable degradation in the beam quality. However, with the carefully designed solenoid cannel we are able end up with a high quality beam of 5 µm normalised emittance with a reasonable focusing strength. The effect of the solenoid misalignment on the beam quality is investigated that determines the required tolerance for the solenoids alignment.

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